DEVICE APPROXIMATING A SHUNT CAPACITOR FOR STRIP-LINE-TYPE CIRCUITS

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

The present invention relates generally to strip-line-type circuits, more particularly to loop transmission lines as shunt capacitors used in such circuits.

2. DESCRIPTION OF THE RELATED ART

Capacitors are one of the basic building blocks for electronic and microwave circuits. In microwave engineering, strip-line-type circuits, including microstrip, strip-line, and multi-layer circuits, can use large metal conductor patches to approximate shunt capacitors. Such patch capacitors can be found, for example, in bias networks of amplifiers, microstrip low pass filters, and matching networks.

As with parallel plate capacitors, the capacitance realized from conductive patches on a microstrip circuit is directly proportional to the area of the patches and the dielectric constant of the substrate. Examples of microstrip patch capacitors are shown in Figure 1. These patch capacitors can occupy a significant amount of surface area, depending on the amount of capacitance required and the type of the substrate used. Use of conductive patch shunt capacitors thus places significant limitations on the layout flexibility and minimum sizes of circuits.

It is thus desirable to construct shunt capacitors that offer more layout options or potential for more compact circuit design or both. The present invention is directed to achieve one or more of these goals.

SUMMARY OF THE INVENTION

In accordance with the principles of the invention, a strip-line-type circuit includes a shunt capacitor that includes a closed conductive loop. The circuit may further include a transmission line connected to the closed conductive loop. The transmission line may be connected to the closed conductive loop at two nodes, in which case the closed conductive loop is divided into two segments, connected in parallel at the two nodes. The impedance of one of the two segments may be substantially larger than the impedance of the other segment, as in the case, for example, where one segment is substantially longer than the other.

The closed conductive loop may be a layer of conductive thin-film pattern formed on a layer of dielectric material, including a loop made of a superconductor such as $YBa_2Cu_3O_{7-d}$ (YBCO) formed on a magnesium oxide, sapphire or lanthanum aluminate substrate.

The circuit may be a multi-layer circuit in which the closed conductive loop extends to multiple layers of conductive patterns.

The closed loop may take on a variety of shapes, including circular, rectangular and swirl shapes.

More particularly, the circuit may be a filter that includes an inductor with each of its ends connected to a closed conductive loop that acts as a shunt capacitor. The filter may include multiple inductors connected in series, with the junctions between the inductors connected to shunt capacitors realized by closed conductive loops.

The filter may be constructed from a variety of materials, including the above-

listed examples. For example, the filter may a band-stop filter having five or more poles constructed from YBCO film on a magnesium oxide substrate no larger than about 50 mm in any dimension.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

Figures 1(a)-(d) show shunt capacitors using microstrip metal patches.

Figure 2 shows a loop transmission line of this invention on a single layer microstrip.

Figure 3 shows an idea lumped element shunt capacitor equivalent circuit.

Figure 4 shows the equivalent circuit of the loop transmission line shown in Figure 2.

Figures 5(a) and 5(b) show, respectively, a single resonator microstrip circuit with shunt patch capacitors and its simulated frequency response curve.

Figures 6(a) and 6(b) show, respectively, a resonator microstrip circuit similar to that shown in Figure 5(a) but using a loop transmission line of this invention, and the simulated frequency response for the circuit in Figure 6(a).

Figures 7(a) and 7(b) show, respectively, a circuit similar to that shown in Figure 6(a) but with single-ended open stub **730** in place of the closed loops **630** in Figure 6(a), and the simulated frequency response for the circuit in Figure 7(a).

Figures 8(a) and 8(b) show, respectively, a circuit similar to that shown in Figure 6(a) but with double-ended open stubs **830, 850** in places of the closed loops **630** in Figure 6(a), and the simulated frequency response for the circuit in Figure 8(a).

Figures 9(a) and 9(b) show, respectively, a microstrip low-pass filter with shunt patch capacitors, and the simulated frequency response of the circuit.

Figures 10(a) and 10(b) show, respectively, a microstrip low-pass filter similar to that shown in Figure 9(a) but using loop transmission line of this invention, and the simulated frequency response for the circuit in Figure 10(a).

Figure 11 shows a sample layout schematic drawing of loop transmission line of this invention in a multi-layer structure.

Figure 12 shows a five-pole band-stop filter using the principles of this invention. The filter is realized on half of an MgO substrate of about 50 mm in diameter and 0.5 mm in thickness.

Figure 13 shows measured results of the five-pole band-stop filter shown in Figure 12.

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the description herein of specific embodiments is not intended to limit the invention to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Illustrative embodiments of the invention are described below. In the interest of clarity, not all features of an actual implementation are described in this specification. It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nonetheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

Referring to Figure 2, one of the simplest embodiments of the invention is a circuit that includes a shunt capacitor realized by a closed conductive loop **200** and a transmission line **210** attached to the loop 200. The transmission line 210 in this case is connected to the loop 200 at two nodes **240** and **250**. The loop 200 can thus be viewed as including two segments **220** and **230** of transmission lines connected in parallel at the nodes 240 and 250. One of transmission lines 230 has nearly zero, but not zero, electrical length, while the other 220 has a larger electrical length selected to approximate the desired capacitance. The electrical length of the transmission line 200 is realized by selection of the physical width and length of the line. The longer segment 220 preferably has a substantially higher impedance than the shorter segment 230.

Referring to Figures 3 and 4, the principles of the invention can be illustrated as follows. From Figure 3, which shows the equivalent circuit of an ideal shunt capacitor with a capacitance C and voltage V across it, one has

$$I_2 = I_1 - I_3 \quad (1)$$

where I_3 is the current following through C from node 1 to ground. That is, the output current I_2 is the difference between input current I_1 and I_3 of capacitor C.

In Figure 4, which shows an equivalent circuit of the circuit in Figure 2, the longer segment 220 is represented by an ideal transmission line **420**, and the shorter segment 430 by another ideal transmission line **430**. V_1 and V_2 are the voltages from node 1 (**440**) and node 2 (**450**) to the ground, respectively. Because the electrical length of the transmission line 230 is nearly zero, $V_1 \approx V_2$ and $I_{S1} \approx I_{S2}$. The output current, I_2, is therefore

$$\begin{aligned} I_2 &= I_{S2} + I_{L2} \\ &\approx I_{S1} + I_{L2} \\ &= I_1 - I_{L1} + I_{L2} \\ &= I_1 - (I_{L1} - I_{L2}) \quad (2) \end{aligned}$$

Comparing Equations (1) and (2), one may select appropriate length and impedance of the long transmission line 220, such that

$$(I_{L1} - I_{L2}) \approx I_3 \quad (3)$$

at a given frequency or frequency band of interest. The result is a closed conductive loop that electrically behaves substantially like a patch shunt capacitor.

One advantage in designing circuits based on the principles of the invention is layout flexibility because the conductive loop may take on a variety of shapes. In addition, accurate computer simulations (using, for example, the ***em*** software package from Sonnet Software, Inc., Liverpool, NY) have shown that for a narrow band

approximation of a microstrip type circuit, using a loop-transmission line to replace a patch shunt capacitor may effectively reduce the area occupied by the circuit.

The circuit based on the principles of the invention may be made of a variety of conductive materials formed on a dielectric layer. Suitable conductive materials include metals such as copper or gold, superconductors such as, niobium or niobium-tin, and oxide superconductors, such as YBCO. Any suitable dielectric material may be used. Examples include alumina, duroid, magnesium oxide, sapphire or lanthanum aluminate. Methods of deposition of metals and superconductors on substrates and of fabricating devices are well known in the art, and are similar to the methods used in the semiconductor industry.

Referring to Figures 5 and 6, a single resonator designed based on the principles of the invention is illustrated (Figure 6) and compared with a single resonator design using patch shunt capacitors (Figure 5). The microstrip filter **500** in Figure 5(a) includes two transmission line segments **510** at the two ends (the input and the output). Between the two segments 510 and separated therefrom by gaps **520** are two conductive patches **530** connected by a zigzag transmission line **540**. The patches 530 primarily function as shunt capacitors, and the transmission line 540 primarily functions as an inductor. In the embodiment shown in Figure 5(a), the substrate has a size of 512 x 256 mils, thickness 20 mils and dielectric constant about 10.

Shown in Figure 6(a), the circuit **600** constructed based on the principles of the invention includes shunt capacitors that are realized by the closed conductive loops **630**. The rest of the circuit 600, including the transmission line segments **610**, gaps **620** and inductor **640**, are similar to their counterparts in Figure 5(a). The circuit 600 is

constructed on the same substrate as the circuit 500 shown in Figure 5(a).

Figures 5(b) and 6(b) show, respectively, the simulated frequency response curves of the circuits shown in Figures 5(a) and 6(a). Both responses include a dominant resonant mode around 2.1 GHz. Where they differ significantly is in the harmonics: The first harmonic for the circuit in Figure 5 is higher than 5 GHz, whereas the first harmonic for the circuit shown in Figure 6 is around 4.6 GHz. Thus, the circuit using closed conductive loops (i.e. Figure 6(a)) may be an suitable alternative to the circuit using patch shunt capacitors in the frequency range near the first harmonic.

It is worth noting that a closed conductive loop behaves quite differently from conductors of other shapes. For example, the circuit shown in Figure 7(a) is otherwise the same as that in Figure 6(a) except that the closed loops 630 are replaced by a single-open-ended stub **730**. The frequency response (Figure 7(b))of the circuit with the stub is drastically different from that shown in Figure 6(b).

As another example, the circuit shown in Figure 8(a) is otherwise the same as that in Figure 6(a) except that the closed loops 630 are replaced by a pair of open-ended stubs **850** and **860**. The frequency response (Figure 8(b)) of the circuit with the stubs is also significantly different from that shown in Figure 6(b). The circuit shown in Figure 8(a) is essentially the one in Figure 6(a) with only a small gap formed in the otherwise closed loop **830**. In theory, if the two open-end stubs 850 and 860 are perfectly symmetrical and balanced and each open-end has exactly half length of the loop shown in Figure 6, the filter may achieve a frequency response similar to that shown in Figure 6(b). However, it is difficult to realize such perfect symmetry in practice, and the spurious response as shown in Figure 8(b) (for example, near 3.3 GHz) would be difficult to avoid.

Referring to Figures 9 and 10, a microstrip low-pass filter designed based on the principles of the invention is illustrated (Figure 10) and compared with a design using patch shunt capacitors (Figure 9). The filter **1000**, shown in Figure 10, includes the closed conductive loops **1020** and **1040**, which substitute, respectively, the conductive patches **920** and **940** in the circuit shown in Figure 9. The total surface areas occupied by the closed loop capacitors 1020 and 1040 in Figure 10 is over 30 percent smaller than that occupied by the patch capacitors 920 and 940 in Figure 9. The transmission lines **1030** in the circuit of the invention differ in shape from those 930 in Figure 9 , but are approximately the same width and total length.

In addition to approximating patch capacitors, close loop capacitors may have other features not available from patch capacitors. Figures 9(b) and 10(b) show, respectively, the simulated frequency response curves of the circuits shown in Figures 9(a) and 10(a). Comparing the responses, both have similar return loss bandwidth, with the filter in Figure 9(a) having 20 dB return loss and the filter in Figure 10(a) having 27 dB return loss. However, the filter in Figure 10(a) produces a much better out-of-band rejection from 3.5 to 6.5 GHz, with steeper slopes on the insertion loss curve Thus, the circuit using closed conductive loops (i.e. Figure 10(a)) may be a preferable alternative to the circuit using patch shunt capacitors.

The principle of the invention is also applicable to multi-layer circuits, i.e., a laminated structure in which multiple layers of conductive patterns are interleaved with dielectric layers. In a multi-layer circuit, the closed conductive loop can be arranged to extend to different layers, offering opportunities for significantly reduced surface area while achieving the same capacitance.

Figure 11 illustrates a shunt capacitor realized by a closed conductive loop in a multilayer structure. In the particular embodiment, the loop **1100** extends into three conductive layers separated by dielectric layers (not shown). A first portion **1120** lies in the lower conductive layer; a second portion **1130** lies in the middle layer, with vertical conductive paths **1140** electrically connecting the two portions. A third portion **1150** lies in the top conductive layer, with another pair of vertical conductive paths **1160** connecting the middle 1130 and upper 1150 portions. This multiplayer structure dramitacally reduces the footprint of the shunt capacitor, In contrast, a patch shunt capacitor in a multilayer configuration would not significantly reduce the footprint of the circuits.

To further illustrate the principles of the invention, a five-pole band-stop filter built on 20 mil thick MGO substrate with YBCO thin-film high-temperature superconductor is shown in Figure 12. The filter **1200** includes a transmission line **1210** that includes four serially connected swirl transmission line portions **1240A, B, C** and **D.** The input and output ends of the filter 1200, as well as the junctions between the pairs of adjacent transmission line portions **1240**, are connected to their perspective shunt branch resonators **1220A, B, C, D** or **E**, which may beidentical to each other. Each shunt branch resonator **1220** includes an interdigitized capacitor **1222** in parallel with an inductor **1224.** The parallel combination may also be realized by a frequency-transformed inductor. The resonator is coupled to the transmission line **1210** by a capacitor **1226.** The resonators may be of any suitable configuration. Examples of the components, including interdigitized capacitors and frequency-transformed inductors are disclosed in the U.S. patent applications serial numbers 08/706974, 09/040578 and 09/699783, which

are incorporated herein by reference.

The input and output ends of the filter 1200, as well as at the junctions between pairs of adjacent inductors 1240, are also connected to their respective shunt capacitors **1230A, B, C, D** and **E**, which are realized by closed conductive loops of varying sizes.

As shown in Figure 12, very compact design may be achieved by using closed conductive loops to realize shunt capacitors. The circuit in this case was constructed within half of an MgO wafer about 50 mm in diameter and 0.5 mm in thickness. Filters of higher orders may also be constructed under such size constraints.

The measured response of the five-pole band-stop filter is shown in Figure 13. The filter's center frequency is at 845.75 MHz, with a bandwidth of about 1.0 MHz.

Thus, by the use of an alternative form of shunt capacitors in planar circuits, the invention offers an opportunity for more flexible circuit layout and more compact circuit size while achieving comparable or superior circuit performance than the designs using conductive patches as shunt capacitors.

The particular embodiments disclosed above are illustrative only, as the invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. The principles of the invention apply generally to all planar circuits, including microstrip circuits, stripline circuits, and coplanar waveguides.. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are considered within the scope and spirit of

the invention. Accordingly, the protection sought herein is as set forth in the claims below.